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THE EFFECT OF LOW-TEMPERATURE STORAGE AND FREEZING ON FRUITS AND VEGETABLES[1]

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The importance of low-temperature storage and refrigerated transportation facilities for food products in the present state of our social and economic system can hardly be estimated. Enormous quantities of foodstuffs which might otherwise be unprofitably utilized or wasted outright are conserved each year by cold storage or are transported in refrigerated cars or ships from the localities where they are grown to communities where they can be utilized. Thus a diversity of diet ranging from tropical fruits to caribou flesh from the Arctic regions is made possible over a large part of the civilized world. The feeding of the large population in industrial centers is rendered much more economical, convenient, and sanitary by the proper application of low-temperature storage to food products.

The mechanical problems of refrigeration have of necessity received much attention, and methods have been perfected whereby constant low temperatures can be readily maintained at a comparatively low cost. The effect of these temperatures on the produce has not received as much attention as the problems seem to warrant. There are, of course, considerable data on the behavior of plant products under low temperatures, which have been obtained by empirical methods. These methods are probably not the best for determining the facts to be used as a basis for a great industry. With the inadequate facilities for careful experimentation and study of physiological problems, it has been the only way for obtaining much of the information urgently needed.

Although the present status of our knowledge of the effect of low temperatures on living plant products leaves much to be desired, a survey of the field of plant physiology shows that some work has been done. It is the province of this paper to take up briefly some phases of the effect of low-temperature storage on fruits and vegetables.

In the commercial storage of these products it is essential that they be kept in such a condition that that group of chemical and physical processes usually associated with living organisms and characterized for want of a better name as "life processes" or "vital activities" can proceed without interruption. At the same time, it is essential that these processes be slowed down as much as possible, so that this portion of the life cycle of the organism will not be completed too quickly and the product become unfit for food through autolytic decomposition or be broken down by the action of micro-organisms.

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[1] Paper read at the symposium on "The Low Temperature Relations of Plants," at Toronto, December 29, 1921.

The physiological problems of commercial cold storage of plant products are, of course, somewhat complex; as in most problems in plant physiology the method of attack has been essentially from a chemical standpoint. The fundamental principle which apparently governs the relation of many of the processes which go on in plants, or which at least seems to explain their relation to temperature, was suggested by Van't Hoff.[2] This rule is that the rate of chemical reaction doubles or trebles for every rise in temperature of 10° C. It has been found that many of the processes which go on in plants take place in accordance with this rule; that is, within limits there is an acceleration of the processes if the temperature is raised and a retardation with the lowering of the temperature. For example, the rate at which CO_2 is given off and oxygen is taken up by plants, which is an indication at least of the rate of respiration, is more rapid at high than at low temperatures. This was shown by de Saussure and by many investigators since his time, working with various kinds of plants (see review by Czapek[3]). It has been demonstrated for apples by Morse,[4] while Gore[5] later carried out a series of respiration experiments on a large number of different kinds of fruits. He found that the factor for the average increase in the rate of respiration for 10° C. rise in temperature, as measured by the amount of carbon dioxide liberated, was around 2.37. From the results obtained by Gore there would seem to be no question but that there is a marked increase in respiration at the higher temperatures. The experiments were, however, only of short duration, and it is doubtful that the processes which result in the taking up of oxygen and the liberation of carbon dioxide and water had reached an equilibrium so that the true measure of the effect of temperature upon these processes could be obtained. In determining the effect of temperature on the rate of respiration, long-time experiments are to be recommended as giving a more accurate measure of this process. The work of Magness[6] indicates that at high temperatures there is an accumulation of CO_2 in fleshy fruits and vegetables and a very low pressure of O_2, while at low temperatures the ratio O_2/CO_2 within the fruit is considerably higher. This might well influence the kind of respiration, and the energy changes might at high temperatures be by intramolecular rearrangement and partial splitting rather than by a breaking down of the molecule to CO_2 and H_2O, while at low temperatures in the presence of larger amounts of oxygen the molecule might be more completely decomposed. Experiments at constant temperatures carried out for long periods will undoubtedly furnish some idea of the amount of CO_2 given off at these temperatures under the conditions existing in the tissue. Some work of this type is in progress at the present time and will without doubt add much to our knowledge of the subject. Some good, simple method of measuring more directly the energy changes involved in respiration is urgently needed.

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[2] Van't Hoff, J. H. Studies in chemical dynamics (Eng. transl.). Pp. 286. London, 1896.

[3] Czapek, F. Biochemie der Pflanzen, 1st ed. 2: 397–399. Jena, 1905.

[4] Morse, F. W. Effect of temperature on the respiration of apples. Jour. Amer. Chem. Soc. 30: 876–881. 1908.

[5] Gore, H. C. Studies on fruit respiration. U. S. Dept. of Agr. Bur. Chem. Bull. 142, pp. 1–40.

[6] Magness, J. R. Composition of gases in intercellular spaces. Bot. Gaz. 70: 308–316. 1920.

Changes in the chemical composition of the product, while not always of value in indicating the constituents used in respiration, are of interest in themselves. The effect of low temperatures on changes which take place in carbohydrates in plants is of especial interest, and a number of investigations have added to our knowledge of this subject. Müller-Thurgau[7] found that in potatoes stored at low temperatures (0°–6° C.) sugars accumulated and starch was broken down more rapidly, while if the temperature was raised (to 8°–10°) the sugar disappeared and starch was formed again. He explains these phenomena by differences in the velocity at which the various reactions involved take place and differences in the optimum temperature, and there is every indication at the present time that this explanation is valid. Appleman,[8] working with white potatoes, found that the carbohydrate changes are dependent on temperature and was able to corroborate much of Müller-Thurgau's work. Hasselbring and Hawkins[9] have shown that the carbohydrate changes in sweet potatoes are apparently similar to those in white potatoes. There is, of course, a higher sugar content in sweet potatoes, the cane sugar especially being much higher at the low temperatures. Sweet potatoes are usually stored commercially at relatively high temperatures (10°–12° C.), and at these temperatures if the roots have been properly cured they may be stored in good condition for a long time. If the temperature is lowered to 0° C., or even to 5° C., they become very susceptible to infection by micro-organisms and soon decay, especially if they are removed from the cold storage to a higher temperature. While it is not within the scope of this paper to discuss this phase of the subject, it is interesting to note the decrease in resistance of these roots at the low temperatures, which parallels the increase in sugar content. It is quite probable that these two reactions are not at all related but are merely concomitant. In the respiration experiments with sweet potatoes, it is shown that CO_2 is eliminated at a much higher rate at 30° C. than at low temperatures.

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[7] Müller-Thurgau, H. Über Zuckeranhaüfung in Pflanzentheilen in Folge niederer Temperatur. Landw. Jahrb. 5: 751–828. 1882.

[8] Appleman, C. O. Biochemical and physiological study of the rest period in the tubers of *Solanum tuberosum*. Md. Agr. Exp. Sta. Bull. 183. Pp. 226. 1914.

[9] Hasselbring, H., and Hawkins, L. A. Physiological changes in sweet potatoes during storage. Jour. Agr. Res. 5: 331–342. 1915. Respiration experiments with sweet potatoes. Jour. Agr. Res. 5: 509–517. 1915. Carbohydrate transformations in sweet potatoes. Jour. Agr. Res. 5: 543–560. 1915.

With stored fruits which contain considerable quantities of acids, the acids seem to be utilized in respiration, especially at the low temperatures, though there may be some decrease in carbohydrate content as well. The acids as a rule break down more rapidly at high temperatures than at low. This has been shown to be the case with apples by Bigelow, Gore, and Howard[10] and by others. It is also true of grapefruit within limits. The sugar content of apples decreases very slowly at low temperatures, while with grapefruit[11] there seems to be a decrease of acidity at the low temperatures, and at high temperatures over long periods the acidity apparently increases and the sugars decrease. This, of course, could be explained as Müller-Thurgau explained the carbohydrate changes in potatoes, or on the theory that the grapefruit uses acids in respiration at low temperatures and carbohydrates at high temperatures with possibly the formation of acids. If space permitted, numerous instances could be cited illustrating this retarding of chemical processes in plants by lowering the temperature. The chemical reactions in plants apparently follow the same rules as chemical reactions *in vitro*, though it is, of course, impossible at present to duplicate, outside the plant itself, all the complex interrelated reactions which go to make up the so-called vital activities of the organism.

With a sufficiently low temperature the water, which, of course, is the main constituent of fruits and vegetables, freezes, and most of these reactions cease. Some few reactions may proceed slowly after the fruit or vegetable is solidly frozen, but most of them will take place only in liquid solution. When the organism is thawed and the water or solute is again liquid, many of the chemical reactions which were going on before freezing are resumed. In the case of most plant parts, however, there is a disorganization of the chemical and physical equilibria, and the processes are not checked and balanced as in the living plant. This, of course, leads to a breaking down and a decomposition of the tissue. The changes in the plant tissue brought about by crystallizing out of the water are discussed by Harvey,[12] Müller-Thurgau,[13] and others who have worked on this particular phase of the problem. In the work on freezing of fruits and vegetables carried on in our laboratories, freezing-point determinations, that is, determinations of the temperature at which the water crystallizes in the plant, have been made on a large number of varieties of some twenty or thirty of the different kinds of fruits and vegetables; altogether some fiteen or twenty thousand determinations have been made. In this work it was found that the freezing points of most of these fruits and vegetables lie between −.5° C. and − 2.5° C. The succulent plants, such as lettuce, cabbage, celery, and cauliflower, freeze at a considerably higher temperature than do potatoes, sweet potatoes, apples, and such produce, which have a relatively high dry weight. Some products, such as nuts, which have a very low water content, have a low freezing point. From our investigations in this field the conclusion seems obvious that all fleshy fruits and vegetables will be killed if exposed to a low enough temperature after ice crystals begin to form in the tissues. Many fruits and vegetables, however, can be cooled to temperatures below their freezing points and have the crystallization of the water actually take place within the tissues without apparent injury, and the occurrence of local injuries, that is, injuries to certain portions of the tissue, due to freezing, is quite common. An illustration of this point is found in the work of Jones, Miller, and Bailey[14] on potatoes. These writers show that a potato may be injured locally by freezing, the death of the cells being followed by browning of the cells around the fibrovascular bundles or in the parenchyma itself. The major portion of the potato, however, might remain sound for a long time. Wright and Harvey[15] and Wright and Taylor[16] corroborated these results in their work on potatoes. It is very doubtful, however, whether ice crystals are ever formed in the potato without injury to the tuber. In this respect they are different from some of the other vegetables and fruits. Apples may be frozen lightly and thawed without apparent injury. Hard, ripe Bartlett pears have been frozen solid, removed from the freezing room, and ripened normally without any indications that the tissues of the fruit had been injured by the solidification of the water. Ripe pears or immature pears of this variety may be seriously injured by freezing. With apples, slight freezing sometimes causes local discolorations around the fibrovascular bundles or dark-colored areas in the tissue. These problems are, of course, under investigation at the present time and are furnishing some interesting information.

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[10] Bigelow, W. D., Gore, H. C., and Howard, B. J. Studies on apples. U. S. Dept. Agr. Bur. Chem. Bull. 94.

[11] Hawkins, L. A. A physiological study of grapefruit ripening and storage. Jour. Agr. Res. **22**: 263–279. 1921.

[12] Harvey, R. B. Hardening process in plants and developments from frost injury. Jour. Agr. Res. **15**: 83–111. 1918.

[13] Müller-Thurgau, H. Ueber das Gefrieren und Erfrieren der Pflanzen. Landw. Jahrb. **9**: 133–189. 1880.

In freezing fruits and vegetables, they may frequently be undercooled far below the freezing point without the formation of ice or without any apparent injury to the tissues. It has been found that potatoes could sometimes be cooled as much as 10° C. below their freezing points, if allowed to remain undisturbed, before the inception of ice formation in the tissue. In certain instances they have been cooled as much as 6° C. below their freezing points and then warmed to temperatures above the freezing point without any evidences of injury. The potatoes, of course, were maintained undisturbed during these experiments.

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[14] Jones, L. R., Miller, M., and Bailey, E. Frost necrosis of potato tubers. Univ. Wis. Agr. Exp. Sta. Res. Bull. 46. 1919.

[15] Wright, R. C., and Harvey, R. B. Freezing point of potatoes as determined by the thermoelectric method. U. S. Dept. Agr. Bull. 895. 1921.

[16] Wright, R. C., and Taylor, G. F. Freezing injury to potatoes when undercooled. U. S. Dept. Agr. Bull. 916. 1921.

A slight jar, such as would be caused by the slamming of the door of the freezing room, tapping the tubers gently with a lead pencil, or dropping them a short distance, promotes the inception of ice formation very readily in undercooled potatoes, and when once freezing begins, injury to the tissues is apparently sure to follow. Apples may be undercooled to a marked degree, and cranberries and cherries withstand temperatures considerably below their freezing points without freezing. Gooseberries have been stored for three months at a temperature of 4° C. below their freezing point and only 11 percent of the fruit were frozen. In general, fruits and vegetables with waxy epidermal coverings may be undercooled much farther than plants in which the cutinized or suberized layer is not so pronounced; for instance, lettuce, celery, and cauliflower are very easily inoculated and will not undercool much below their freezing points. Other factors besides these waxy coverings apparently also influence the degree of undercooling, as plugs of potatoes with the cut surfaces exposed will undercool as much as do whole tubers. It is quite possible that the concentration of the cell sap has considerable to do with these phenomena. Wright and Taylor have shown that the rate at which potatoes are cooled influences the degree below their freezing points to which they can be cooled without freezing. To put it briefly, a very rapid or a very slow fall in the temperature is not favorable to low undercooling. Other factors as yet unrecognized are undoubtedly concerned in these phenomena.

A survey of the work on plant physiology, and especially on the phases relating to low-temperature storage and freezing, impresses one with the aptness of the statement frequently made, that "plants are water with some other things in it." This is especially applicable to fruits and vegetables which are commonly placed in cold storage. The water content of this type of produce varies from about 95 to 65 percent. The chemical processes in the plant are in a watery solution, and, as far as they have been investigated, follow much the same course as they do outside the plant. In freezing, the apple or potato behaves in about the same way as does a solution as regards undercooling, inoculation, and the crystallizing out of the water. We have, of course, in this aqueous solution a great many interrelated reactions going on at the same time, and knowledge of each process and of its relation to the other processes is necessary for a good understanding of the subject.

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